

EVOLVING APPROACHES TO PULSED X-RAY SOURCES

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Abstract. Production of pulsed radiation in the keV-to-MeV range for simulation of the nuclear weapon effects uses pulsed power generators of $1 - 10 \text{ TW}^1$. Radiation in the high-energy (gamma and hot) part of the spectrum has been obtained using intense electron beams incident on the solid target of high Z material to produce radiation with continuous bremsstrahlung spectrum. Magnetically driven plasma implosions have been used to obtain radiation in the keV (cold) part of the spectrum, characterized by strong line emission. The efficiency of radiation, required for DTRA tasks, relative to stored pulser energy, is only a few percent. Radiation yields in the range of 5 to 60 keV are especially low, regardless of which method of radiation production is used. This article discusses pulsed power diodes employed for production of pulsed x-rays.

I. INTRODUCTION

The spectrum of the pulsed radiation for simulation of the nuclear weapon effects (NWE) ranges from keV to MeV and the yields range from low tens to hundreds of kilojoules, from x-ray simulator drivers of $1 - 10 \text{ TW}^{1,2}$. Radiation in the high-energy gamma (0.3-20 MeV) and hot (30 – 300 keV) part of the spectrum is obtained using intense electron beams incident on the solid target of high Z material to produce radiation with characteristic bremsstrahlung spectrum². Cold radiation (1 – 15 keV range) is obtained using high current self-pinching plasma implosions of sufficiently high electron temperature to generate strong K-line emission. The evolution of pulse power technology and drivers that can generate the hot and cold radiation have been described in Ref. 1. DTRA continues to pursue innovations in the pulsed power drivers. This paper describes the development of radiation sources: high voltage electron beam diodes and plasma implosion diodes, as radiation sources for the NWE community.

Further studies, using electron beam systems to produce hot radiation with shorter pulse duration and with higher dose capability, as well as warm² radiation (in 15 – 60 keV range), are continuing. Plasma implosion systems are investigated, in conjunction with the pulsed power drivers, to produce greater radiation yield (and higher fluence on target). Approaches combining advanced load designs with novel power flow stages are investigated to

increase fluence in the spectral range from 5 keV to more than 15 keV, unattainable with present approaches.

The representative radiation goals of the DTRA programs for cold x-rays, include initially hundreds of kilojoules of Ar K-line and higher energy lines from a large simulator³. Regarding the hot x-rays an important goal today is the reduction of the $\sim 40 \text{ ns}$ pulse duration in order to increase the deposition rate in test materials and to drive the bremsstrahlung x-ray energy down below 100 keV.

II. EVOLUTION OF RADIATION SOURCES FOR NUCLEAR WEAPONS EFFECTS TESTING

Over the nearly forty years of developing flash x-ray simulators, DTRA has always attempted to produce both the cold and hot x-rays from the same simulator. The hot x-ray simulators were developed first in the sixties and the bremsstrahlung diodes worked best with sub-100 ns vacuum power pulses. Thus, most of the developments of the PRS diodes were also with this short power pulse.

A. Hot X-Ray and Gamma Sources

Penetrating radiation simulators employ electron beam and high-Z target interaction to produce bremsstrahlung radiation, with a spectrum determined by the voltage applied across the electron beam diode. The applied voltage also determines the efficiency, ϵ , of the radiation relative to the energy in the beam⁴: $\epsilon = (3 \times 10^{-4} ZT_0)/(1 + 3 \times 10^{-4} ZT_0)$, where T_0 is the electron kinetic energy in units of mc^2 . The lowering of the efficiency, as the diode voltage decreases, led to a requirement for large diode current to achieve doses of radiation sufficient for testing. The self-magnetic field of current in the diode leads to pinching at the anode, where the electric fields can be neutralized by the plasma formation, greatly increasing the current density and, consequently, the radiation dose.

Diodes for gamma sources. The earliest x-ray simulators built for NWE testing were the high voltage gamma simulators. Operating at voltages up to 20 MV, the high impedance diodes have large A-K gaps and produced a stiff, low v/γ , e-beam with forward directed radiation pattern. The term v/γ is the ratio of the current to the critical current, I_c , given by the expression $I_A = 17,400 (\beta/\gamma) x(R/D)$ (amperes), where β is the electron velocity normalized to the speed of light and $\gamma = (1 - \beta^2)^{-1/2}$.

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Radiation is produced efficiently in high voltage diodes, sufficient for some of the early NWE testing requirements. The gamma diodes, associated with the two most powerful simulators, Aurora (closed now) and Hermes III (at SNL), operated at diode voltages up to 8 and 19 MV, respectively.

Pinched Beams. Differential absorption, associated with the hot x-ray effects is a major factor in the NWE testing of electronic circuits. To better simulate these effects, radiation sources, with the bulk of radiation in the spectral range of 60 to 300 keV, were required. This led to lower voltage (< 2 MV) generators and to the development of low impedance diodes with small anode-cathode gaps⁵. At these high currents, of the order of 1 MA, the critical current, I_C , is exceeded when $I_C = 8500\beta\gamma R/D$ and where R/D is the diode radius to electrode gap ratio. The large self-magnetic field and the production of ions in the anode-cathode gap lead to strong beam pinching at the anode. These diodes provide the required beam power density to satisfy radiation test requirements (up to 100 krad[Si]).

Ring diodes. Many testing requirements did not need the high doses of the pinched beam, but simply moving the target further away from the source was very inefficient due to $1/r^2$ fall-off. Therefore, for larger area, lower dose applications, a ring beam diode^{6,7} was developed, as

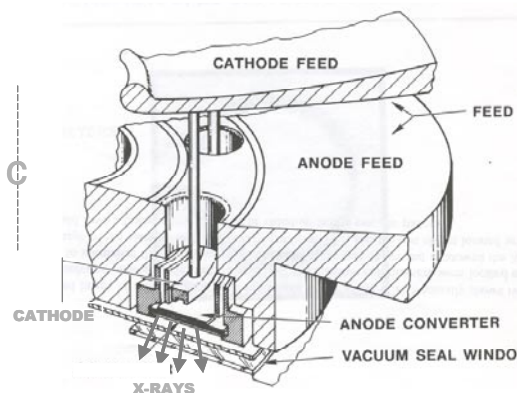


Fig. 1. Post-hole convolute feeding continuous ring cathode, which emit two electron beams in Blackjack 5 facility.

shown in Fig. 1, producing a more appropriately distributed radiation pattern. Simulators with the electrical output of 8 TW produced 20 krad(Si) over 1000 cm^2 using these ring diodes.

Series diodes. To reduce the end-point energy of the spectrum, without going to very low voltage, high current machines, series diodes^{8,9} were developed. By re-configuring the electron beam diode into two or three diodes in series, with each anode serving as a radiation

converter, the end point energy was reduced to 300 - 500 keV, from a power pulse in the 1 - 1.5 MV operating range. The dose produced by the two stage series diode⁹ is not reduced (relatively to single diode radiator) on a 16 cm diameter test plane. It is reduced only by 30 %, over the same area, when the end-point voltage is dropped to 500 keV, by the series triode.

Narrow pulses. The radial velocity of a beam undergoing pinching within the diode cathode also provides a method for shortening radiation pulses^{5,10}. The average beam pinch collapse velocities at sub-MA currents can be up to few cm/ns¹⁰. By using low Z anode material at large radius and shielding this outer area of the anode, only the radiation from the inner area emerges, resulting in shortening the radiation front to, typically, $< 5 - 10$ ns. About half of the diode beam energy is utilized¹⁰.

B. Cold X-Ray Production.

In contrast to hot x-rays, cold x-ray sources are evolving from the softer to hotter parts of the spectrum, using hot plasma as the source of radiation, rather than electron beam - solid target interactions. Early attempts to develop cold x-ray sources included dense plasma focus (DPF) implosions¹⁷, single hollow cylinder¹⁸ or wire discharges¹⁹. Later, these sources evolved, with cylindrical arrays of thin wires and gas shell implosions²⁰ becoming sources of low keV radiation, satisfying many user needs. In all these cases, the discharge current is made to flow through a plasma, resulting from the heating of the wire or gas loads at the beginning of the current pulse. Detailed analyses of implosion dynamics, heating and radiation continue to be studied¹⁴.

DPF and Tandem Puff. Discovered in the early 1960's, the dense plasma focus (DPF)^{11,15} is also an effective cold x-ray source. It is a z-pinch formed at the end of a coaxial set of electrodes, following an axial rundown, during the development of the peak current. The current is initiated along an insulator in the breech, moves axially as a snow-plough into the background gas of deuterium, neon, or argon. As the current builds up to its peak value and the plasma current sheath expands, it creates a vacuum inductance storing the magnetic energy. At the end of the center electrode, the current sheath implodes onto the axis

Depending on the load, the heating mechanisms involve thermal heating, as well as electrons and ion acceleration. The plasma temperature tends to be one to two keV and emits both thermal and line radiation, as well as neutrons when using deuterium or tritium gas¹¹. The DPF has produced a higher efficiency of Ne K-line radiation relative to capacitor bank energy, than the sub-100 ns pulse-forming generators, although with a longer radiation pulse¹⁶. Comparison of the outputs from these sources is shown in Fig 2.

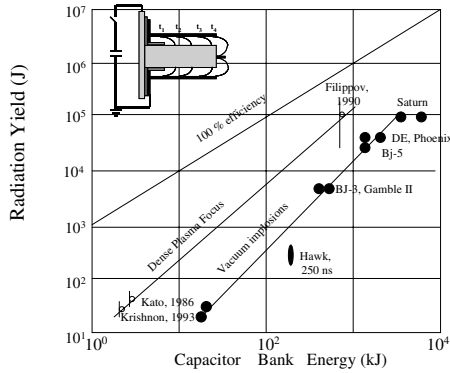


Fig 2. Ne radiation yields from DPF and PRS sources.

A modifications of the DPF configurations (“Tandem Puff”), shown in Fig. 2 insert, uses flashboard-plasmas to initiate the current without the re-strike-prone insulator in the breach.¹⁷ This configuration has produced pulses as short as 12 ns.

Single wire. The earliest example of a fast (~ 10 ns) cold x-ray emission from (hollow) wires, using parallel plate capacitor discharge driver is shown in Fig. 3¹². The concept of using the non-thermal component of the very-high-atomic-number plasma radiation source (PRS) to provide radiation with photon energies in 10’s-of-keV is based on NRL Gamble II and Physics International (PI) OWL II single-wire-load research of the 1970s. For wires with the highest atomic numbers (tungsten), substantial non-thermally-excited radiation yields

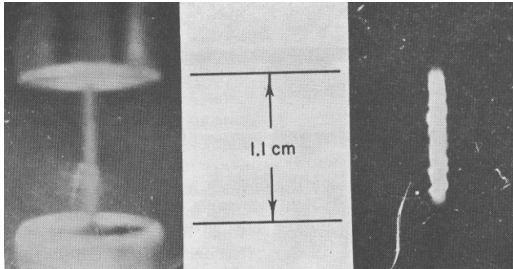


Fig. 3. Visible light image of the cylinder (left) before the discharge and x-ray radiation formed by a pinhole (right)

(>100 J) are produced in the 5- to 100-keV band. In the limited cases studied, this non-thermal radiation greatly exceeds the soft spectral component of bremsstrahlung generators of comparable current and, unlike the sources of cold x-rays. X-ray production mechanisms are described in many references, as in Ref. 19, for example. bremsstrahlung sources, lacks a hard radiation component¹⁸.

Gas puff and wire arrays. Implosions of cylindrical wire arrays and gas shells have been developed into practical. This reference shows that the output of a twin shell gas

puff load, similar to the one shown in Fig. 4, scales with current,

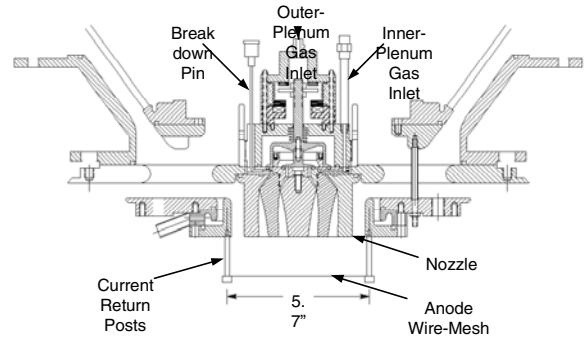


Fig. 4. Gas injection nozzle for double shell mass distribution in the AK gap.

as I^2 to I^4 , for up to 15 MA, yielding 270 kJ of Ar K-line and higher²⁰

The parameter of interest to simulator users is fluence, of specified uniformity, over desired area. The fluences, F , associated with yield, Y , for a given testing area, A , is given by the expression $F(\text{cal/cm}^2) = KY(\text{kJ})/A(\text{cm}^2)$, where K is proportional to the degree of non-uniformity of the illumination of a plane of area A by a point source ($K = 6$ and 12 for $\pm 5\%$ and $\pm 10\%$ departure from uniform exposure, respectively).

C. Warm X-Ray Production

Inverse diode. The lowest energy solid converter diodes have used an e-beam which flows back into the direction of the pulsed power from a highly transparent, wire grid cathode fed by a central stalk. This diode, shown in Fig. 5, was developed for the Maxwell Modular Bremsstrahlung

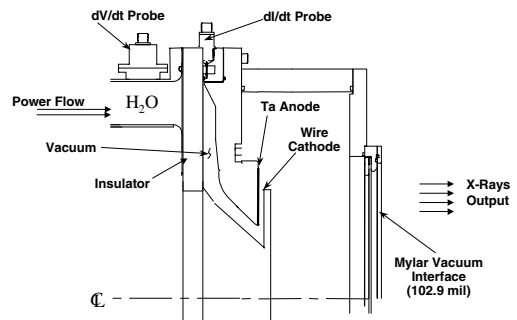


Fig 5. Illustration of the MBS inverse-diode used to produce a low average energy bremsstrahlung source.

Source (MBS) simulator and served as a high fidelity source; although the fluence was quite low, at less than a mcal/cm.²

Reflex triode. Warm spectrum radiation (above 10 keV) has been produced by using bremsstrahlung diode designs which minimize the self-absorption in the anode converter and allow for maximum transmission from the converter to the test volume²¹. The disadvantage of this approach, as applied to simulators, is that the end-point of the bremsstrahlung spectrum extends into 100's of keV, needed to maintain reasonable efficiency.

PROSPECTS

The long history of radiation source development reviewed here reflects both the requirements, associated with the pulsed radiation testing, as well as significant technological advances that were needed to meet these requirements. Promising ideas, such as described in Ref. 22 provide fuel for further improvement in the fidelity of sources and in the search for means to reduce the cost of these sources. Such ideas as compression of magnetic flux and current multiplying stages, discussed at this Conference, may provide better cold x-ray -- and more intense -- warm x-ray sources.

REFERENCES

- [1]. K. Ware, R. Gullickson, J. Pierre, R. Schneider, and I. Vitkovitsky, "Development of Affordable Technologies for Large X-ray Simulators", IEEE Trans. Plasma Sci., vol. 28, no.5, pp. 1397 – 1404, Oct. 2000.
- [2]. "Radiation Test Facilities and Capabilities" Fourth Edition, January 1997, *Limited Distribution*, Defense Special Weapons Agency, Alexandria, VA 22310-3398
- [3]. P. Sincerny, et al, "Concepts for Affordable High Current Imploding Plasma Generator", Proc. 12th IEEE International Pulsed Power Conference, IEEE Cat.No. 99CH36358, pp. 479–483, 1999.
- [4]. I. Smith, G. Rice, H. Aslin, "Advanced Flash X-ray System", Technical Report AFWL-TR-68-113, Vol.1, p.198: originally from: H. Koch, J. Motz, Rev. Mod. Phys. vol. 31, p. 920, (1959).
- [5]. E. Blaugrund, G. Cooperstein, S. Goldstein, "Relativistic electron beam pinch formation process in low impedance diodes", Phys. Fluids, 20, 1185 – 1194 (1977)
- [6]. J. Shannon et al., "The Application of the Magnetically Insulated Splitter to High Power Electron Beams", IEEE Int. Conf. On Plasma Sci. San Diego, CA. p. 4, May 1983.
- [7]. D. Blumquist, et al, "Saturn, a large area x-ray simulator", Proc 6th PPC'87, pp. 310 – 321 (1987).
- [8]. J. R. Boller et al., Bull. Am. Phys. Soc., 27, 991 (1982)
- [9]. J. Meachum, J. Riordan, P. Sincerny, S. L. Wong, "Triple Series Diode Development" Defense Special Weapons Agency Tech. Rep. DNA-TR-92-200-V1, 1997.
- [10]. E. Blaugrund, G. Cooperstein, "Intense focusing of relativistic electrons by collapsing hollow beams", Phys. Rev. Lett., 34, 461 – 464, (1975)

- [11]. Y. Kato, S. Be, "Generation of soft x-rays using a rare-gas plasma focus and its application to x-ray lithography", Appl. Phys. Lett., **48**, 686- 688 (1986).
- [12]. I. Vitkovitsky, "X-Ray Emission from Exploding Wires", Phys. Fluids, **7**, No. 4. Apr 1963. Fig. 12 is reproduced from: W. Faust, g. Leavitt, J. Shipman, I. Vitkovitsky, "Exploding Conductors", Final Report to DASA, 1960 – 1963, Naval Research Laboratory Report 6009, 31 Oct. 1963.
- [13]. D. Mosher, et al, "X-Radiation from High-Energy-Density Exploded Wire Discharges", Apl. Phys. Lett. **23**, 429 (1973)
- [14]. A. Velikovich et al., "High Energy Photon Radiation from Z-pinch Plasma", submitted to Plasma Physics (2001)
- [15]. N. Filippov et al., "Megajoule scale plasma as efficient X-ray source", Phys Lett. A 211, 168-171 (1996). Also see N. Filippov, et al, "Fillipov Type Plasma Focus as Intense Source of Hard X-Rays ($E_x \sim 50$ keV)", IEEE Trans. Plasma Sci., vol. 24, 1215-1223, (1996)
- [16]. K. Ware, DTRA, 1994, unpublished
- [17]. J. Thompson, P. Davis, H. Murphy, et al, "Z-Pinch Characteristics of the Tandem Puff", presented at the Advanced Pulsed Power Conference, BDM International, Inc. Albuquerque, NM, 31 July, 1990.
- [18]. D.L. Johnson, et al., NRL Memorandum Report 3207, 1976 and D. Mosher and D. Colombant, Phys. Rev. Lett. **68**, 2600(1992).
- [19]. K.G. Whitney, et al., "Basic Considerations for Scaling Z-Pinch X-Ray Emission with Atomic Number", J. Appl. Phys. 67, 1725 – 1735, 1990.
- [20]. H. Sze et al., "First Results for an Argon Z-pinch at Currents > 15 Megamps", submitted to Phys. of Plasma Lett. (2001)
- [21]. V. Decaux, et al, "High Dose Bremsstrahlung Experiments Using the Warm X-Ray Reflex Triode," presented at HEART Conf., March 1999.
- [22]. A. Velikovich, et al, "Model of enhanced energy deposition in a Z-pinch plasma", Phys. Plasma, vol. 7, 3265-3277 (2000)